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THE EFFECT OF THE DIAMETER OF HANDWHEELS, USED AS WHEELS, UPON THE TIME REQUIRED FOR ADJUSTMENT

A Thesis
Submitted to the Faculty
Of
Purdue University
By
James Ottis House, Jr.
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Of
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~~18104~~

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ABSTRACT

The purpose of this study was to investigate the effect of the diameter of handwheels, used as wheels, upon the time required to adjust the handwheel to a specified degree of accuracy for several torques.

Five handwheels, ranging in diameter from four to fourteen inches, with axial loads ranging from 6.05 to 108.15 inch-pounds, were used for this experiment. Thirteen operators were used. Each operator was required to use both hands to adjust a pointer in a counter-clockwise direction through an arc of 30 degrees to within an accuracy range of one degree. The time required to make each adjustment was measured on a tape recording kymograph. Ten readings were taken for each torque and each handwheel, except for the two smaller handwheels of four-inch and five-inch diameters. No readings were taken for the heaviest load of 108.15 inch-pounds for these two handwheels, since it was evidently unreasonable to expect the operators to adjust these handwheels under this condition.

It was found that the selected experimental parameters were adequate to give statistical significance to the data collected. Within the limits of this investigation, the four-inch handwheel appeared to result in the slowest operator performance while the ten-inch handwheel appeared to result in the speediest operator performance.

THE EFFECT OF THE DIAMETER OF HANDWHEELS, USED AS WHEELS, UPON THE TIME REQUIRED FOR ADJUSTMENT

INTRODUCTION AND PURPOSE

A survey of the literature shows that several studies covering the field of handwheel selection have been conducted. Extensive studies[1] concerned with the problem of selecting the proper handwheel to be used on radar equipment for the tracking of targets have been conducted under the auspices of the National Defense Research Committee. However, there has been relatively little experimentation undertaken from the standpoint of determining the proper size of handwheel to be used on machine tools.

Davis[2] conducted an experiment in order to "determine the factors making for optimum control and speed of usage of handwheels, cranks and crossbars under the condition of application involving single settings of indicators within close tolerance limits".

The author's investigation was undertaken in order to further study a particular segment of the problem of handwheel selection so that the machine designer might have reliable and complete information, within certain experimental parameters, for the selection of the optimum size of handwheel

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1. The Foxboro Company, Foxboro, Mass., Inertia, Friction and Diameter in Handwheel Tracking, O.S.R.O. Report No. 3454.

2. Davis, L. E., Custom-Tailor Your Manual Controls, Machine Design, 21, No. 9:127-130, 1949.

which would result in the speediest operator performance.

The purpose of this study was to investigate the effect of the diameter of handwheels, used as wheels, upon the time required to adjust the handwheel to a specified degree of accuracy for several torques.

APPARATUS

The equipment used to conduct the experiment is described below:

1. Five cast iron handwheels (Figure 1) of the following diameters were used: four-inch, five-inch, seven-inch, ten-inch and fourteen-inch. These handwheels were fitted with solid type handles and were considered to be representative of handwheels usually available to the machine designer. Although this experiment was conducted using the handwheels as wheels instead of cranks, it was decided that actual conditions would be better simulated by leaving the handles fitted to the handwheels.
2. A shaft, on which the handwheels could be fastened, connected through a chain of gears to a light wooden pointer (Figure 2). This system of gearing caused the operator to rotate the handwheel through 150 degrees in order to move the pointer through an arc of 30 degrees. This shaft rotated through sleeve bearings, which in turn were fastened to a rigid wooden structure.
3. A device (Figure 3), similar to a prony brake, was used to apply axial loading to the shaft. A cylindrical wooden pulley was fastened, between the bearings, to the shaft. A length of automobile type brake lining was passed over the pulley. One end of the brake lining

Handwheels

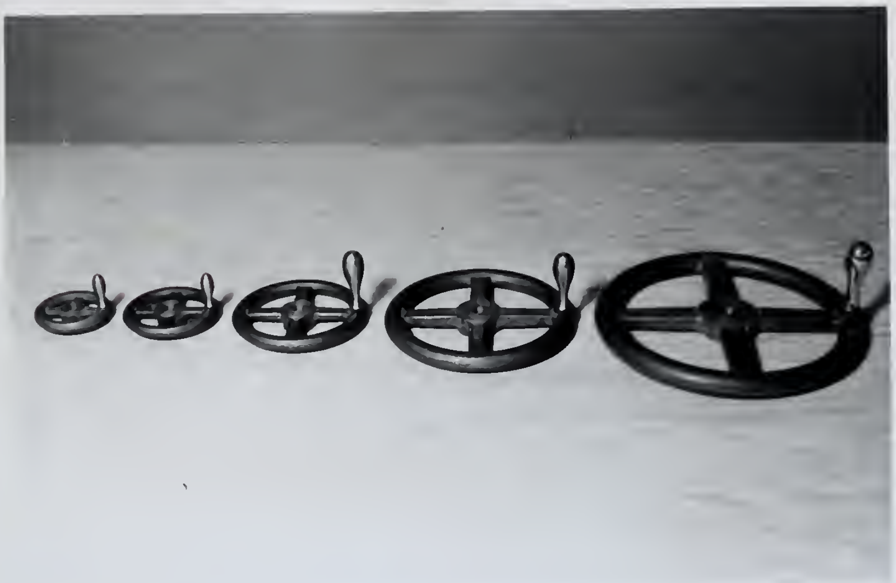

FIG. 1

Shaft and Pointer

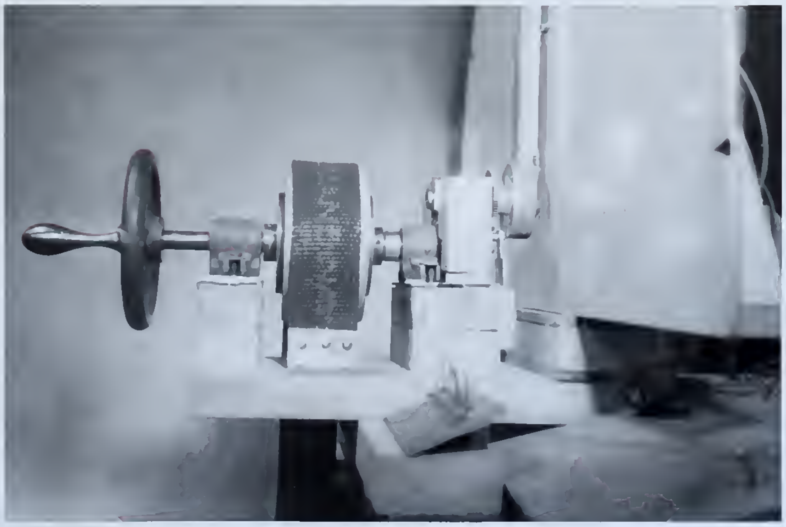

FIG. 2

Braking Device

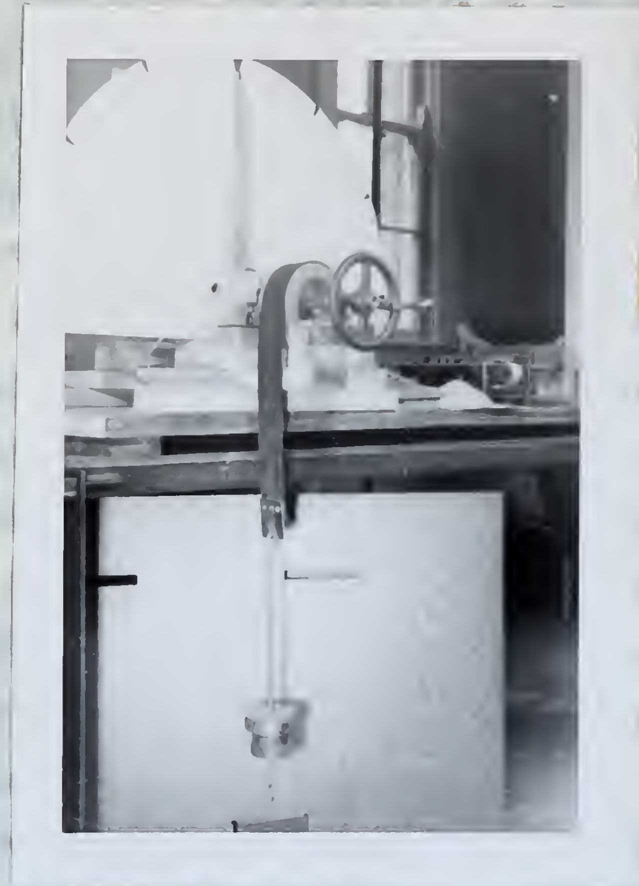

FIG. 3

was fastened to the base of the apparatus and to the other end a hanger was attached. Removable steel weights could be placed on this hanger to provide the necessary braking action.

4. A semi-circular plywood backboard (Figure 4) was securely fastened in a plane parallel to and directly behind that which was generated by the rotating pointer. The backboard was painted white, and black markings[3] were provided to indicate the required position of the pointer.

5. A stimulus light (Figure 4) was fastened on top of the backboard directly over the pointer's vertical position. This light consisted of a 6 watt, 115 volt bulb which illuminated a red glass lens.

6. A tape recording kymograph (Figure 5), manufactured by the Lafayette Instrument Company, Lafayette, Indiana was used to record times. The tape was advanced at a rate of 22.496 cm. per second when the kymograph was operated.

7. A "cat's whisker" was attached to the pointer such that an electric circuit would be completed when the pointer was within the specified accuracy range. When this circuit was completed a system of relays caused a stylus on the kymograph to be actuated.

[3] Paterson, A. G. and Tinker, M. A., Black Type versus White Type, Jour. Applied Psychol., 15: 248-251, 1931.

Backboard, Pointer and Stimulus Light

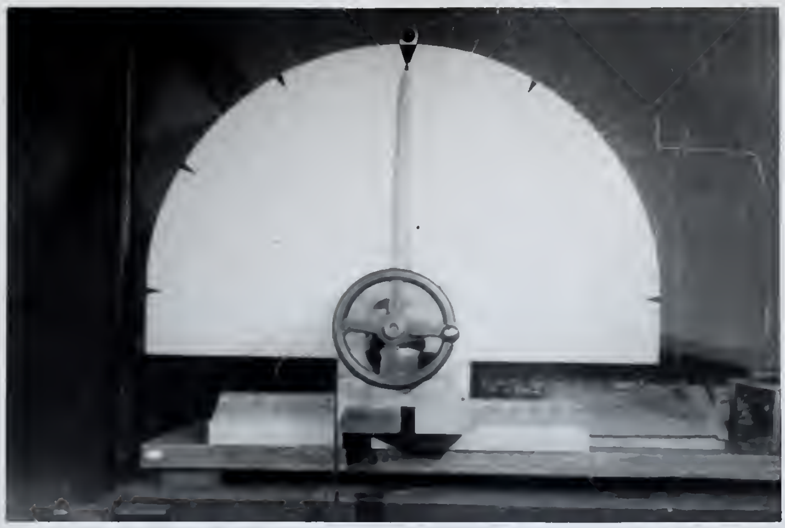

FIG. 4

Kymograph

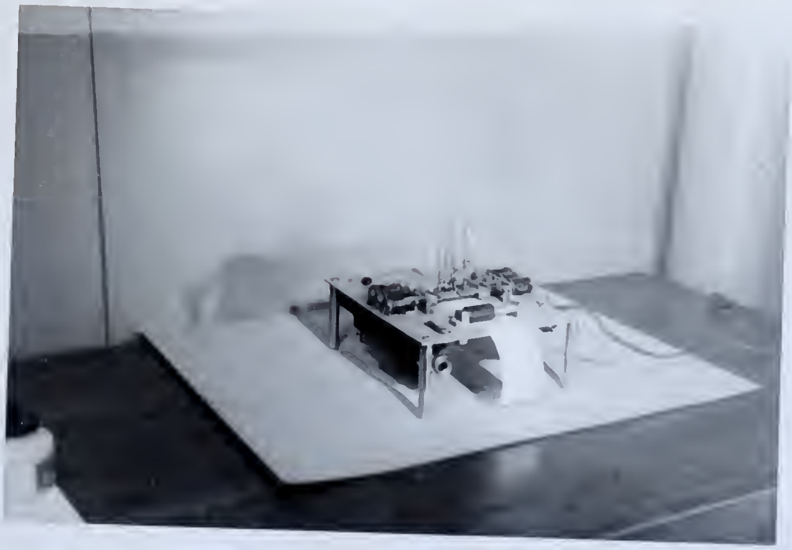

FIG. 5

8. In order to minimize the variable due to the operator's reaction time, it was decided to measure time from the instant the handwheel was grasped until the pointer was finally positioned within the specified accuracy range. A capacity-operated relay[4] (Figure 6) was constructed for the purpose of actuating a stylus on the kymograph at the instant the operator touched the handwheel. A circuit diagram of this device is included in Figure 7; the operation of this capacity-operated relay is explained in the following[4]:

> As the antenna-to-ground capacity is increased, the amplitude of oscillation can be made to increase. The 6J7 tube is used as an oscillator. The rectifying action of the grid of the 25L6 relay tube causes a rectified a-c-voltage, equal to the peak value of oscillating voltage on the cathode of the 6J7, to be built up in the grid-leak and condenser. The oscillator oscillates on each positive cycle of plate voltage, but during this time the 25L6 tube, whose plate connects to the other side of the line, is non-conducting. The negative charge built up on the grid of the 25L6 does not leak off during the non-conduction period, however, and hence is effective in controlling the relay current during the alternate conduction periods.

Figure 8 illustrates the electric circuit used to operate the kymograph.

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4. Electronic's Engineering Manual; New York, McGraw Hill.

Capacity-Operated Relay

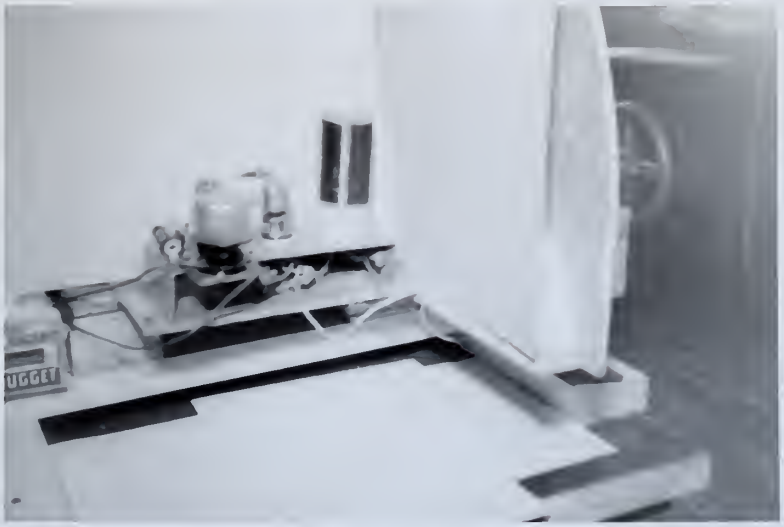
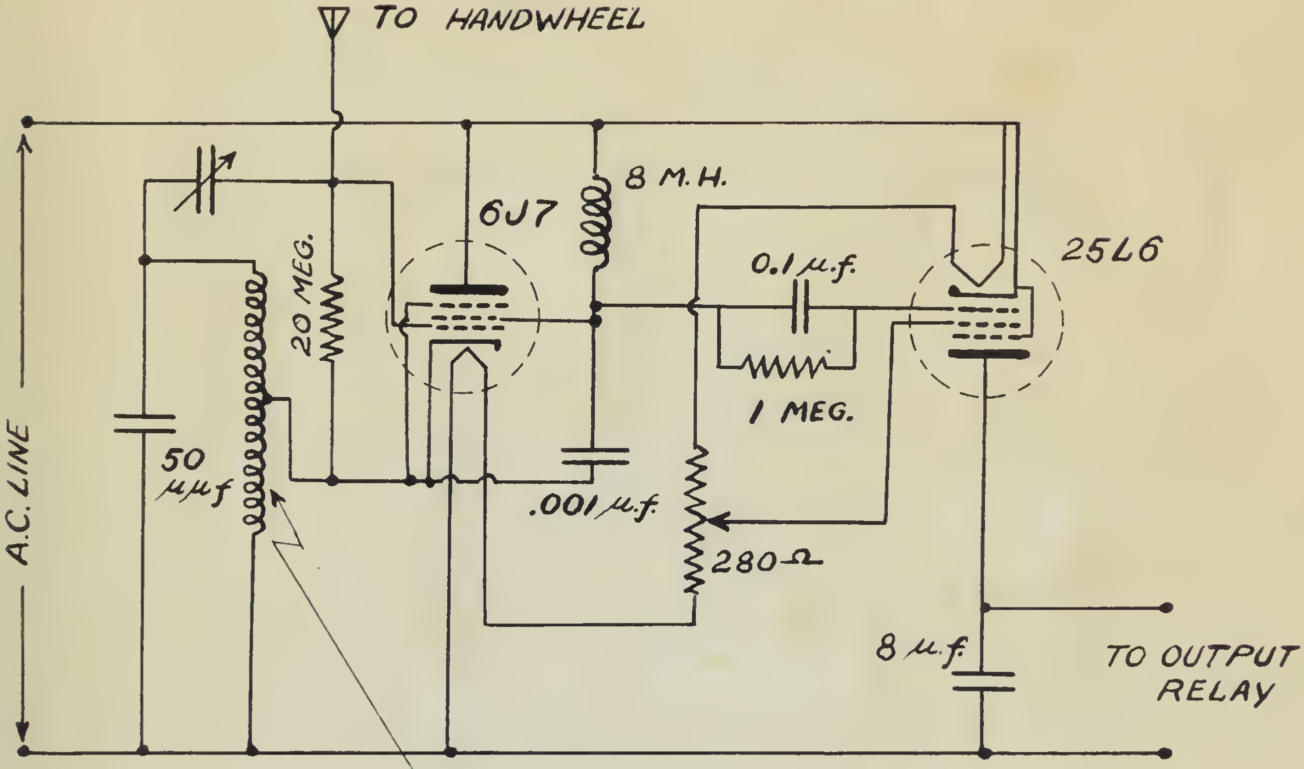


FIG. 6

CIRCUIT DIAGRAM OF CAPACITY-OPERATED RELAY



2" dia., 100 turns of No. 20 wire, center tapped.

FIG. 7

CIRCUIT USED TO OPERATE KYMOGRAPH

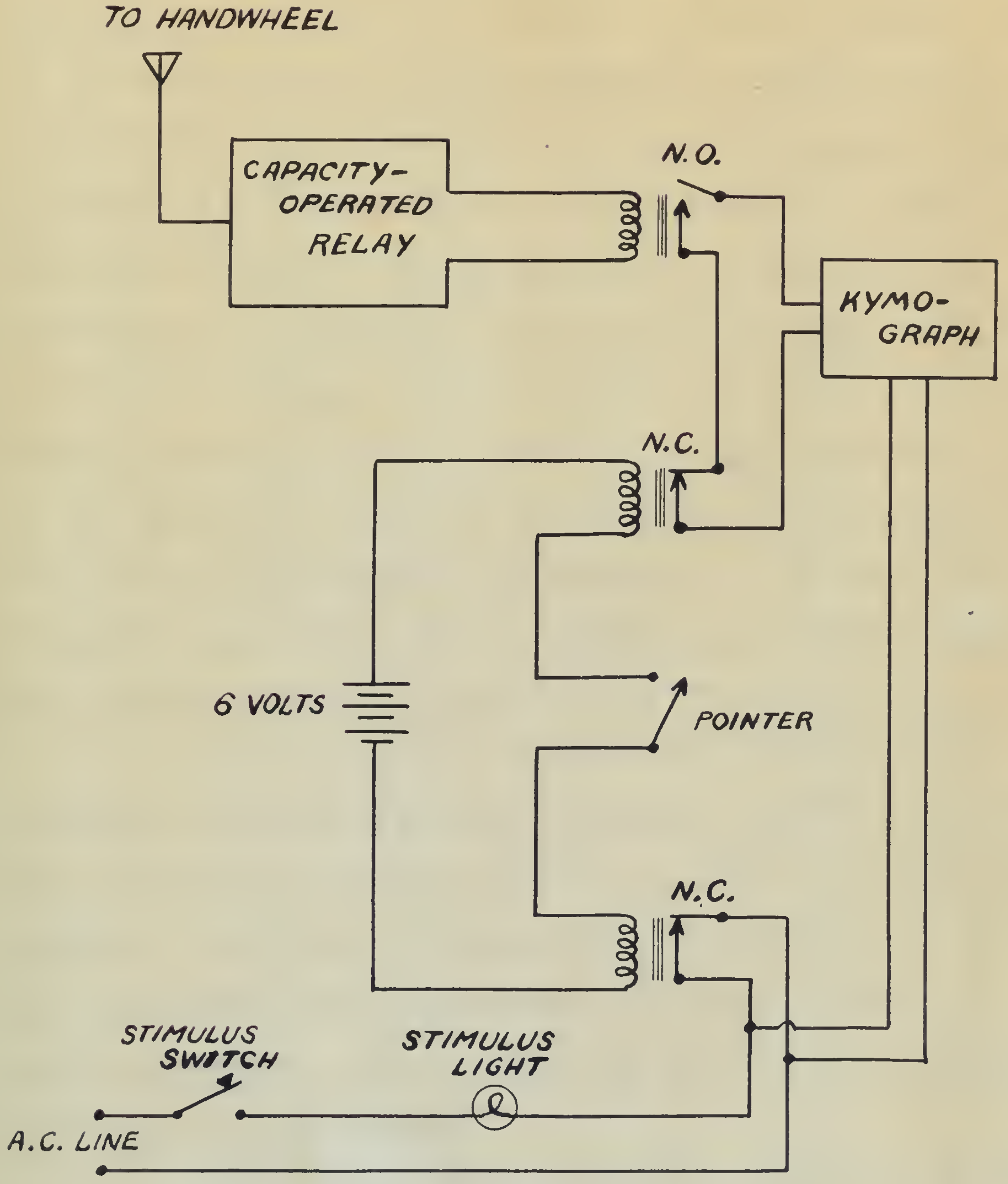


FIG. 8

PROCEDURE

Care was taken to eliminate or minimize all of the many unwanted variables in this experiment. As stated before, the apparatus was set up so that the reaction time of the operator was not included in the measured time. A large screen, installed behind the apparatus, was provided in order to eliminate glare and/or distractions from outside the building. A constant source of lighting was provided by a floodlight which was placed above and to the rear of the operator. Platforms were provided so that the various operators could be positioned similarly with respect to the handwheel shaft. A rubber floor mat was provided so that all the operators had good footing. The experiment was conducted in a large, well ventilated room and the temperature was maintained at approximately 70 degrees F.

Since it was not practical to conduct a long training period for the operators, the handwheels and torques were presented in a random manner in order to minimize the effect of training. The sequence of presentation of torques and handwheels was established by the use of tables of random numbers[5]. Table 1 shows the order of presentation of torques and handwheels.

Figure 9 contains a sample of tape from the kymograph and illustrates the method used to obtain time readings.

[5] Lindquist, E. F., Statistical Analysis in Educational Research; New York, Houghton Mifflin Co., 1940.

Table 1

ORDER OF PRESENTATION OF HANDWHEELS AND TORQUES

Operators	HANDWHEELS AND TORQUES				
1	7 in. JHDBF	10 in. BDHFJ	14 in. BFJDH	4 in. FHJD	5 in. HJFD
2	4 in. FDHJ	7 in. BDJFH	10 in. HJDFB	5 in. FDJH	14 in. BJHFD
3	7 in. JBHDF	14 in. JFDHB	10 in. HFDBJ	4 in. FJDH	5 in. DHFJ
4	5 in. HJFD	4 in. HDJF	14 in. JFHDB	10 in. BFJHD	7 in. DJFHB
5	14 in. DJHFB	7 in. JDBHF	5 in. JFDH	4 in. FHJD	10 in. HJFBD
6	7 in. FDHBJ	4 in. JHFD	10 in. HBFDJ	5 in. FJDH	14 in. JBFHD
7	10 in. BJHDF	4 in. DFJH	7 in. HFJBD	5 in. FJDH	14 in. DBJFH
8	14 in. DFHBJ	4 in. HDFJ	7 in. DHFJB	10 in. DJBHF	5 in. HJDF
9	7 in. BHFJD	10 in. HJFBD	14 in. BFHDJ	4 in. HDFJ	5 in. JFHDB
10	4 in. JDFH	10 in. FBJHD	7 in. JHDFB	14 in. HBJDF	5 in. JHDF
11	5 in. FHJD	10 in. HDJFB	14 in. JFDBH	7 in. HDBJF	4 in. JFHD
12	5 in. HFJD	10 in. JFBDH	7 in. FBDHJ	4 in. HJFD	14 in. BHJFD
13	5 in. HDJF	4 in. HFDJ	14 in. JHDBF	7 in. DFJHB	10 in. JBFHD

Key:		
	B	108.15 in-lbs.
	D	55.35
	F	28.20
	H	17.20
	J	6.05

Sample of Tape from Kymograph

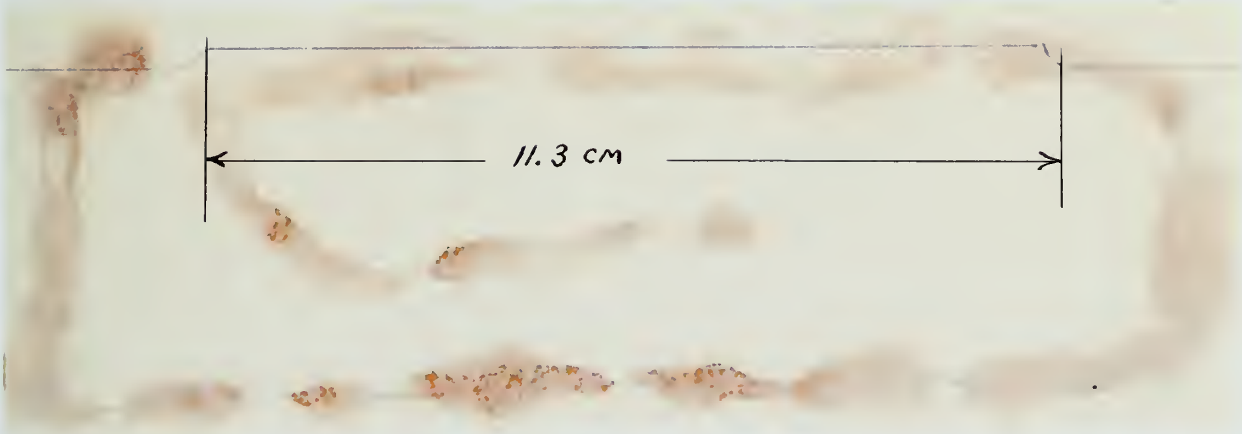


FIG. 9

The operators were chosen at random; no attempt was made to select operators to represent a particular population. All the operators were males and were in good physical condition. Table 7, Appendix A, gives the age, weight, height and elbow height of the operators.

Five torques, ranging from 6.05 to 108.15 inch-pounds, were used to apply axial loads to the handwheels. This range of torques was selected after measuring the torques on several representative machine tools in Michael Golden Machine Tool Laboratory, Purdue University.

The handwheels were assembled to the shaft so that their handles would be in the lower left-hand quadrant when the pointer was at the 30 degree position.

Each operator was given the following instructions prior to commencing a run:

"You will stand directly in front of the handwheel and position yourself so that your knuckles, when your clenched fists are held together and your elbows are held against your sides with your forearms parallel to the floor, will just touch the handwheel shaft.

"The pointer is now at the 30 degree mark. When the red stimulus light, which is mounted on top of the board, goes on you will grasp the rim of the handwheel with both hands and turn it in the counter-clockwise direction until the tip of the pointer is within the 1 degree accuracy range, as indicated by the mark on the board. When the

pointer is correctly positioned, the stimulus light will go out. When the kymograph is stopped, return the pointer to the 30 degree position, remove your hands and wait for the next stimulus light.

"Work as rapidly and accurately as you can. If you overshoot, return the pointer to the 1 degree mark. All of your readings will be used in analyzing the data.

"You are allowed two trials, at the lightest load, before taking readings for each handwheel.

"Remember, you are to use both hands, and are to work as rapidly and accurately as you can. Have you any questions?" (Answers were given as required).

RESULTS

The mean times required for each operator to adjust the pointer to within the required accuracy range of one degree are tabulated in Tables 2 to 6 inclusive. Detailed data taken for each operator are included in Tables 8 to 20 in Appendix A.

The data were first subjected to an analysis of variance technique[6] to determine whether or not the variations due to the handwheels, their axial loads, the operators, and the various interaction effects were significant. A summary of the results of these calculations are given in Appendix B. Sample calculations to illustrate the mathematical technique employed are also included in Appendix B. The results of this analysis showed, beyond reasonable doubt, that the handwheels differed significantly among themselves and that the loads also differed significantly among themselves. This analysis further showed that the variation due to the operators was, beyond reasonable doubt, due to factors other than chance alone. In addition, it was found that the interaction effects were, beyond reasonable doubt, due to factors other than chance alone.

[6] Snedecor, George W., Statistical Methods Applied to Experiments in Agriculture and Biology; Ames, Iowa, Collegiate Press, 1937.

Croxton, Frederick E. and Cowden, Dudley J., Applied General Statistics; New York, Prentice-Hall, Inc., 1939.

Table 2

Mean Times in Hundredths of Seconds For Adjustment of Pointer

FOUR INCH HANDWHEEL

Operator	Torque (In.-Lbs.)				
	55.35	28.2	17.2	6.05	T_o
1	963	503	556	466	2488
2	909	950	689	582	3130
3	1008	713	561	486	2768
4	1063	684	548	471	2766
5	909	571	482	474	2436
6	973	732	725	637	3067
7	719	464	468	426	2077
8	1200	691	713	490	3094
9	615	636	476	390	2117
10	1382	861	677	778	3698
11	738	419	550	325	2032
12	702	434	358	323	1817
13	732	683	478	569	2462
T_t:	11913	8341	7281	6417	T: 33952

Table 3

Mean Times in Hundredths of Seconds For Adjustment of Pointer

FIVE INCH HANDWHEEL

Operator	Torque (In.-Lbs.)				
	55.35	28.2	17.2	6.05	T_o
1	739	454	431	376	2000
2	750	534	434	420	2138
3	791	425	414	511	2141
4	873	634	739	525	2771
5	744	502	501	425	2172
6	591	550	493	414	2048
7	436	377	223	388	1424
8	731	504	617	313	2165
9	489	432	343	324	1588
10	743	489	420	484	2136
11	460	541	456	321	1778
12	596	490	608	325	2019
13	570	507	598	620	2295
T_t:	8513	6439	6277	5446	T: 26675

Table 4

Mean Times in Hundredths of Seconds For Adjustment of Pointer

SEVEN INCH HANDWHEEL

Operator	Torque (In.-Lbs.)					
	108.15	55.35	28.2	17.2	6.05	T_o
1	667	615	481	660	564	2987
2	895	608	375	303	479	2660
3	987	603	451	607	527	3175
4	593	607	489	442	509	2640
5	688	551	561	436	473	2709
6	797	822	754	598	449	3420
7	679	466	339	323	332	2139
8	816	917	640	589	423	3385
9	604	601	339	279	334	2157
10	548	595	539	482	381	2545
11	673	671	567	510	456	2877
12	648	411	411	290	295	2055
13	567	520	415	437	347	2286
T_t:	9162	7987	6361	5956	5569	T: 35035

Table 5

Mean Times in Hundredths of Seconds For Adjustment of Pointer

TEN INCH HANDWHEEL

Operator	Torque (In.-Lbs.)					
	108.15	55.35	28.2	17.2	6.05	T_o
1	635	608	546	592	467	2848
2	436	453	324	436	273	1922
3	871	688	612	454	386	3011
4	684	727	595	541	468	3015
5	519	526	289	361	283	1978
6	666	609	506	662	509	2952
7	712	452	416	511	368	2459
8	535	680	390	531	379	2515
9	556	480	426	440	354	2256
10	737	508	646	513	471	2875
11	533	559	507	314	549	2462
12	499	390	442	342	317	1990
13	515	464	435	464	433	2311
T_t:	7898	7144	6134	6161	5257	T: 32594

Table 6

Mean Times in Hundredths of Seconds
For Adjustment of Pointer

FOURTEEN INCH HANDWHEEL

Operators	Torque (In.-Lbs.)					
	108.15	55.35	28.2	17.2	6.05	T_o
1	672	571	523	501	429	2696
2	588	452	448	437	465	2390
3	753	627	508	581	602	3071
4	834	884	742	636	763	3859
5	641	568	518	483	408	2618
6	778	704	714	696	642	3534
7	384	336	389	349	412	1870
8	728	740	456	439	484	2847
9	683	445	488	410	362	2388
10	593	572	648	593	546	2952
11	427	449	390	487	482	2235
12	602	375	452	399	428	2256
13	634	756	643	700	766	3499
T_t:	8317	7479	6919	6711	6789	T: 36215

After these data had been analyzed, further statistical techniques[7] were employed to fit curves to the data and to test the curves for goodness of fit. The results of these computations are tabulated in Appendix C, Table 26. A sample of these calculations is included in Appendix C in order to fully illustrate the statistical technique employed. Figures 10 to 15 show curves for operator performance for the handwheels and torques selected.

Two handwheels, the four-inch and the five-inch, were not subjected to the full range of axial torques. It was found to be wholly unrealistic to expect the operators to manipulate these handwheels when they were subjected to the highest axial load of 108.15 inch-pounds. In presenting the curves included in this paper, no attempt at extrapolation of data beyond the range of experimentation has been made. According to Snedecor[8]: "Extrapolation is mostly a guessing game".

It was shown that a straight line gave an adequate fit for the data for the four-inch, five-inch, ten-inch, and fourteen-inch handwheels and that a parabola gave an adequate fit for the data from the seven-inch handwheel.

The results of this study are briefly summarized:

1. The handwheels that were used were found to differ significantly among themselves.

[7] Croxton and Cowden, (op. cit.).
[8] Snedecor, (op. cit.).

2. The torques selected, for axial loading, were found to differ significantly among themselves.
3. The operators were found to differ significantly among themselves.
4. The following interaction effects were found to be significant:
    - (a). Handwheels versus torques.
    - (b). Handwheels versus operators.
    - (c). Torques versus operators.

FITTED CURVES FOR TIME VS TORQUE FOR ALL LENGTHS

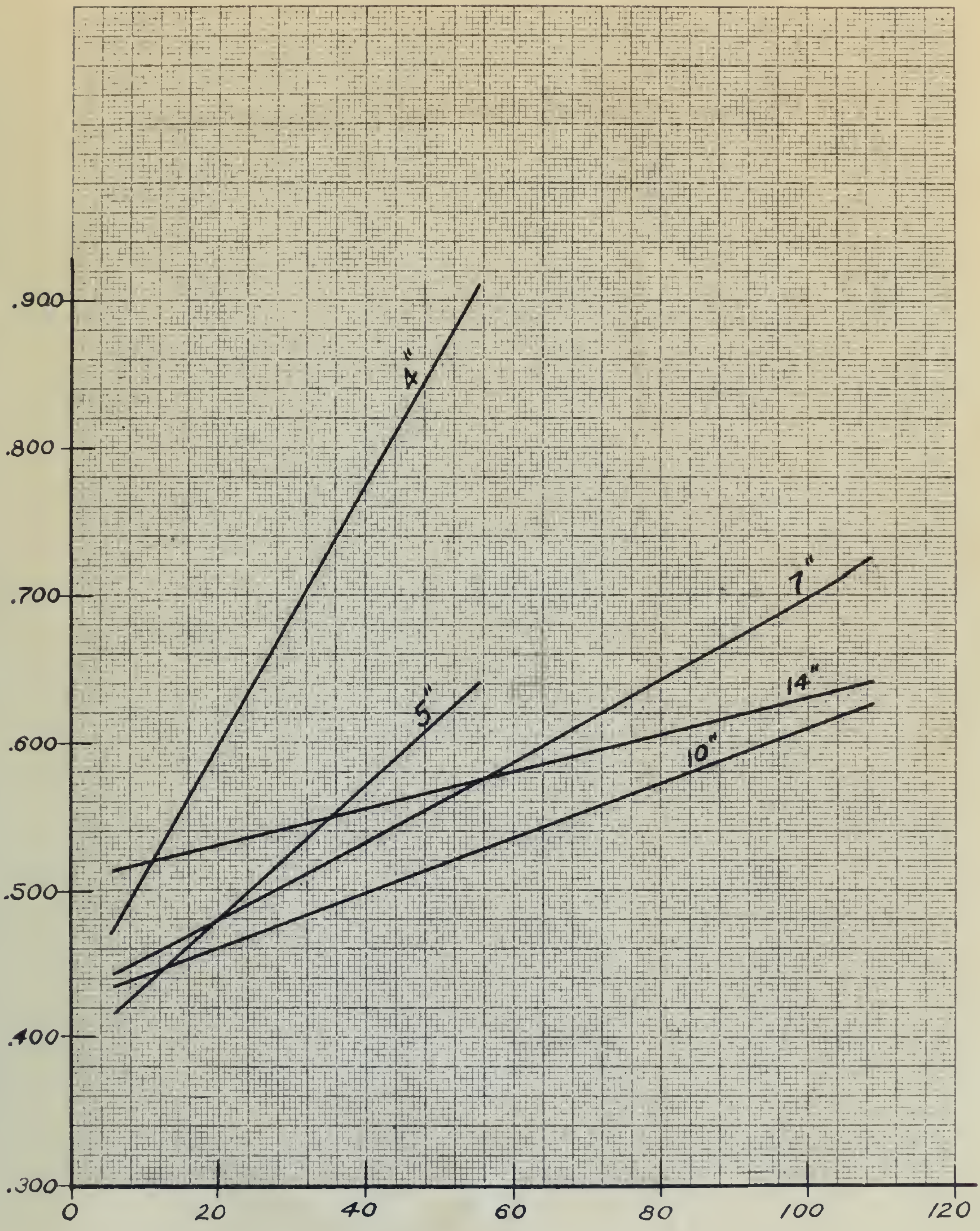


FIG. 10

FOUR-INCH HAND-WHEEL - MEAN TIME FOR ALL OPERATORS

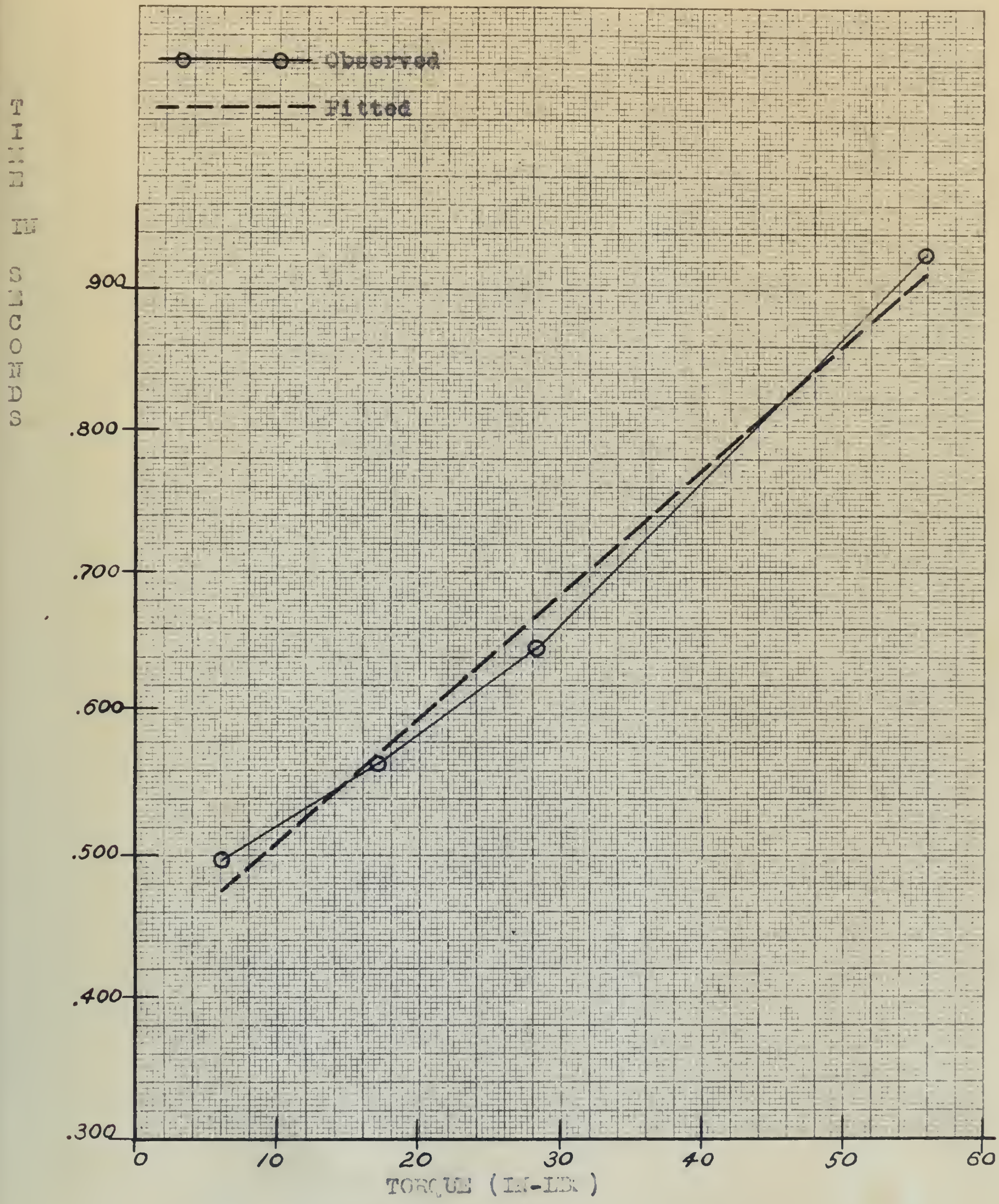


FIG. 11

FIVE-INCH HANDWHEEL - MEAN TIMES FOR ALL OPERATORS

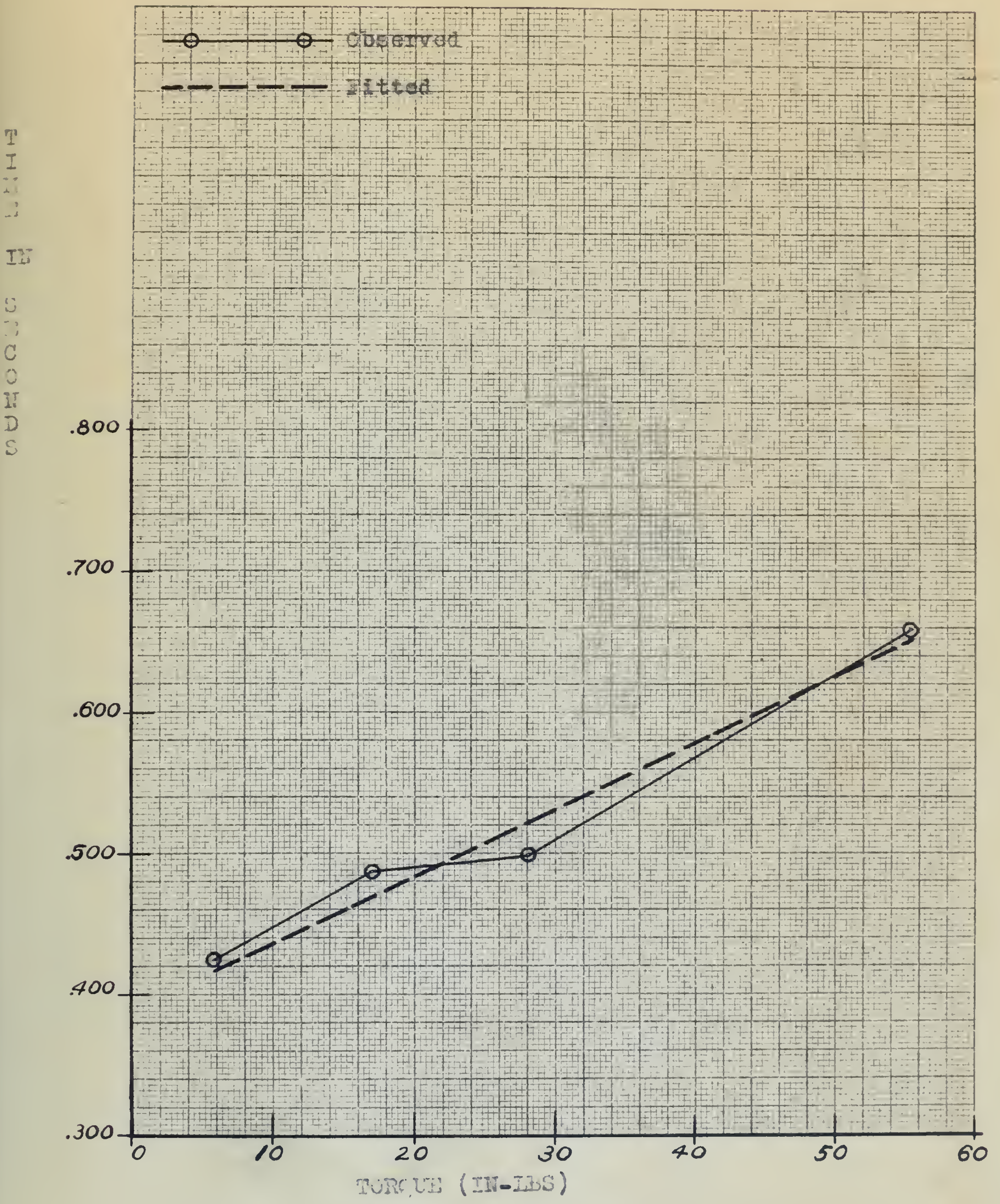


FIG. 12

SEVEN-INCH HANDWHEEL - MEAN TIME FOR ALL SUBJECTS

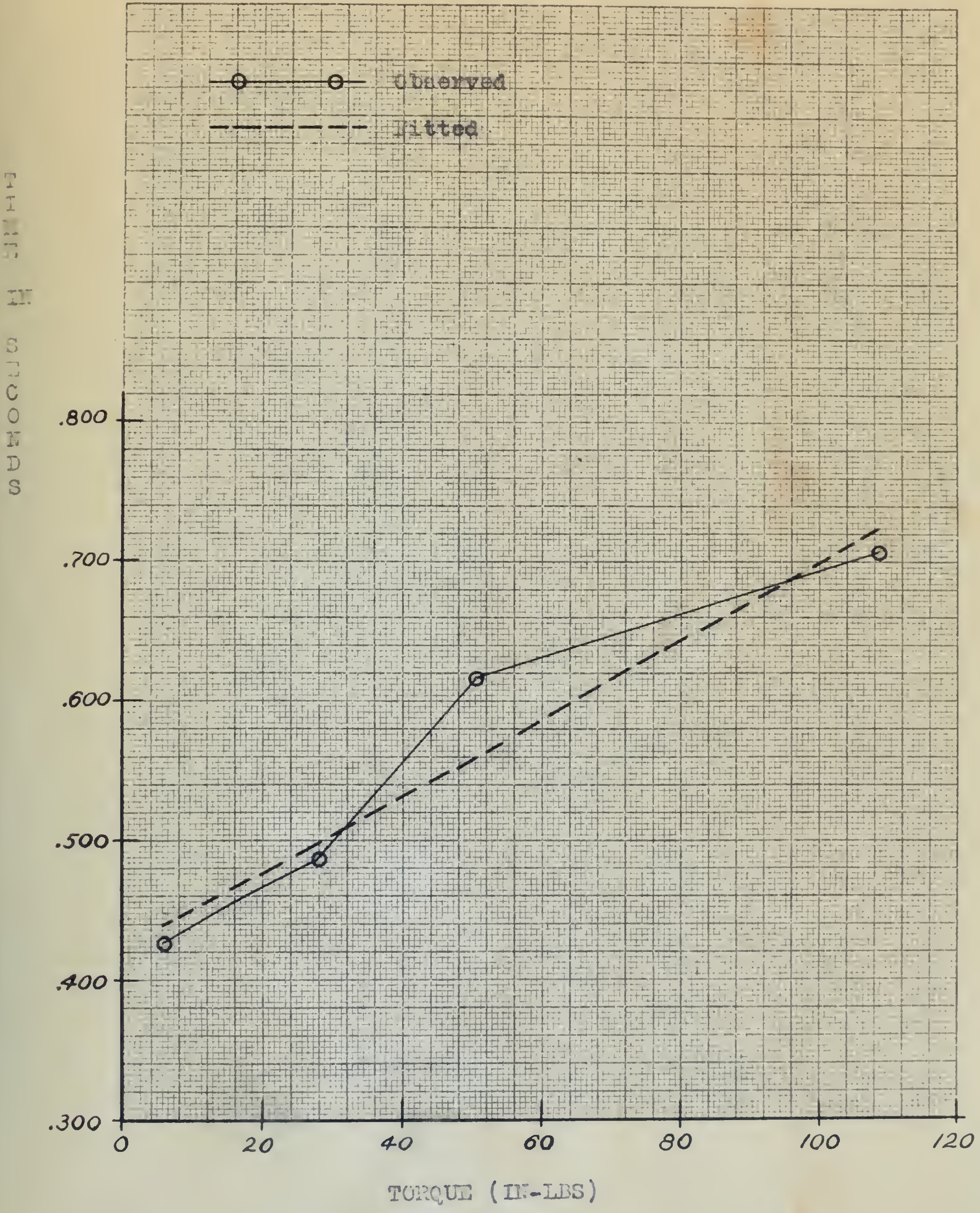


FIG. 13

TWO-INCH [illegible] - MEAN TIMES FOR ALL OPERATORS

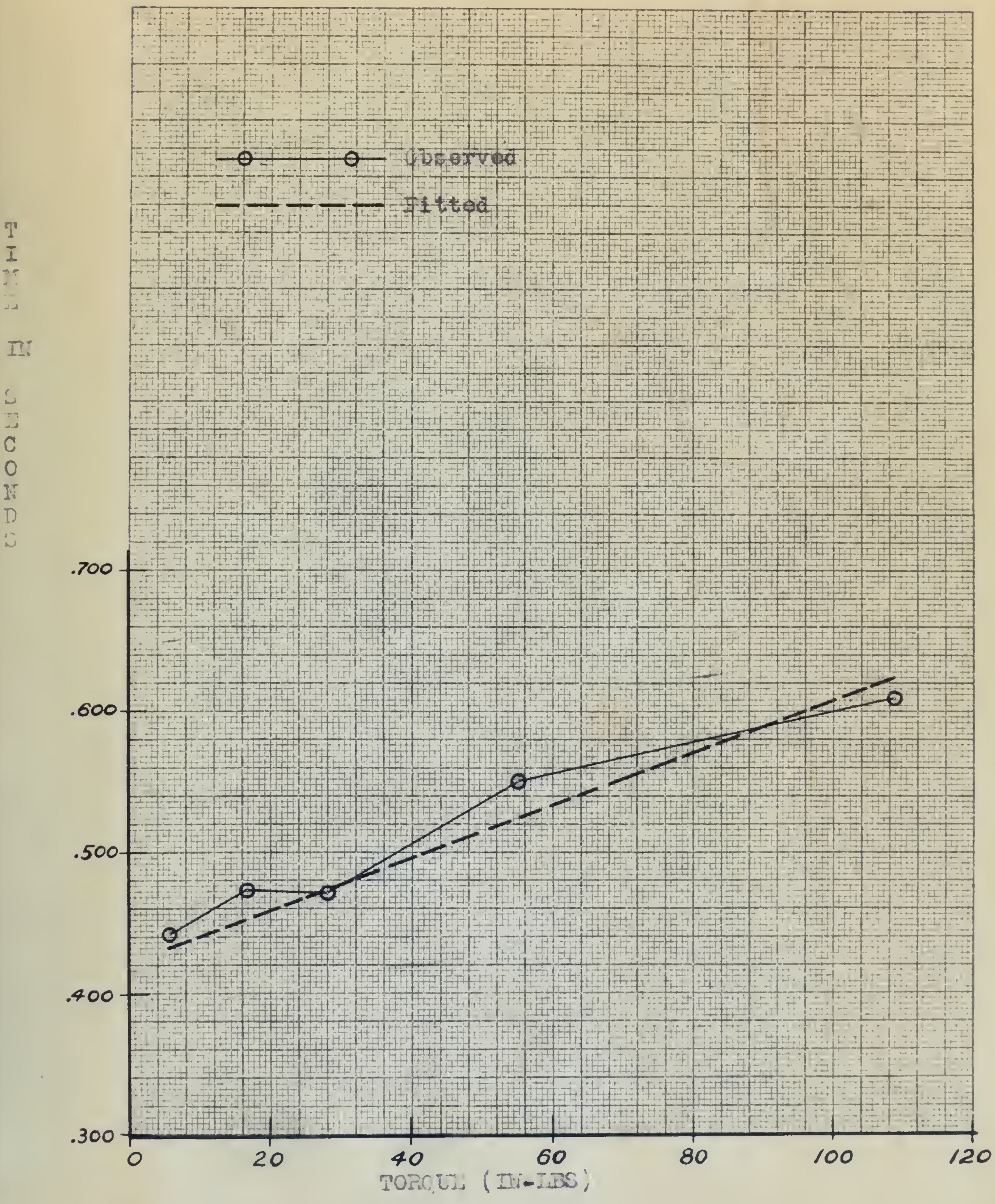


FIG. 14

FOURTEEN-INCH HANDWHEEL - MEAN TIMES FOR ALL OPERATORS

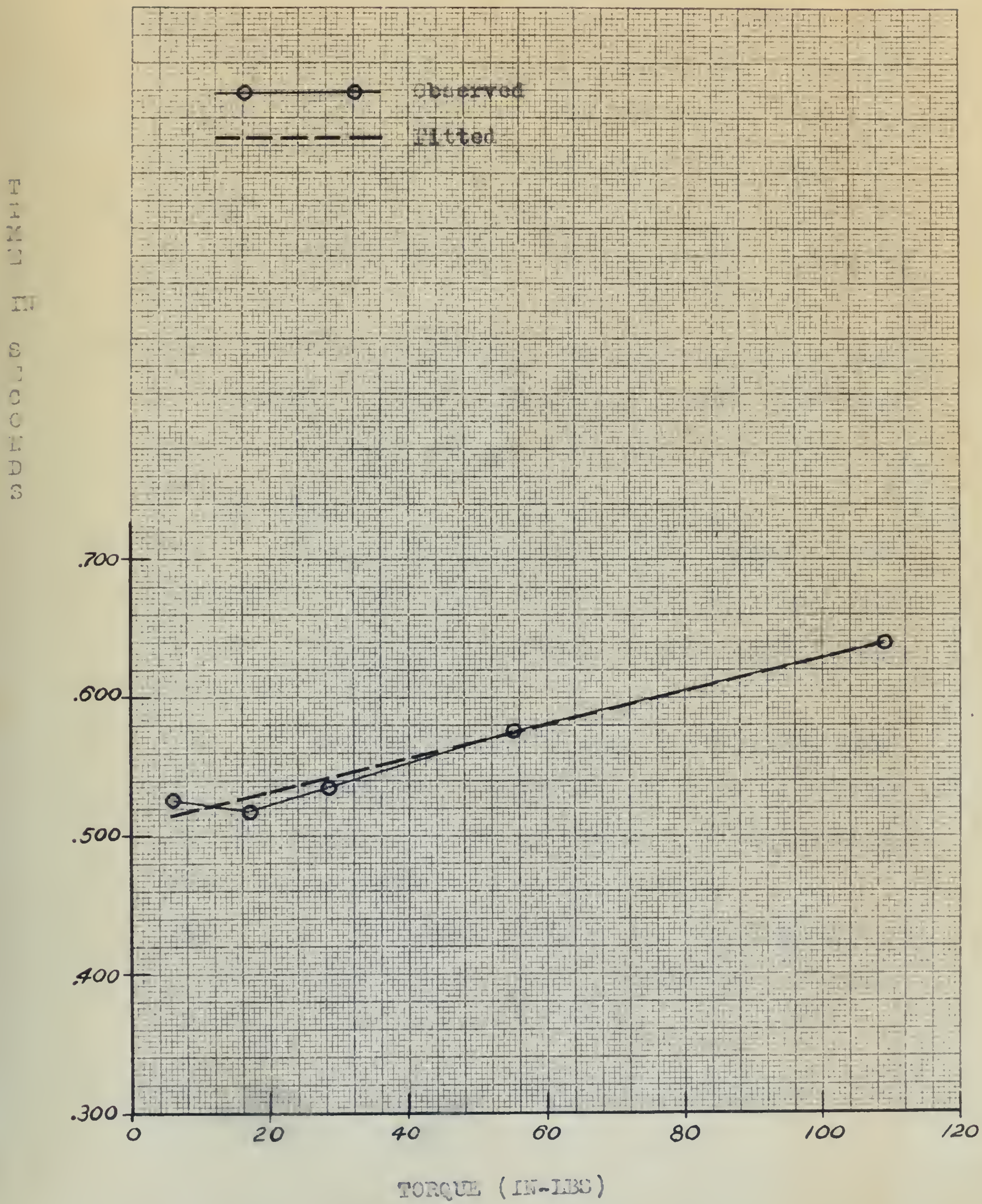


FIG. 15

CONCLUSIONS

The conclusions from this study may be summarized as follows:

1. The size of handwheel, used as a wheel, was a pertinent variable and did affect the time required to adjust the pointer to the required accuracy range of one degree.
2. The axial load was a pertinent variable and did affect the time required to adjust the pointer to the accuracy of one degree.
3. Since the effect of training was minimized by the process of randomization, it was concluded, without proof, that the variation among the operators was due to individual differences[9].
4. From an inspection of the curves and using time of adjustment to the specified accuracy as a criterion, the following conclusions concerning the use of handwheels, used as wheels, were made:
   (a). Of the five handwheels that were studied, the four-inch handwheel appeared to result in the slowest operator performance for practically all the torques that were included in this experiment.
   (b). Of the handwheels studied, the ten-inch handwheel appeared to give optimum results for the range of torques that were investigated.

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[9] Tiffin, Joseph, Industrial Psychology; New York, Prentice-Hall, Inc., 1947.

APPENDIX A

Characteristics of Operators (Table 7) And Times Required For Each Operator to Adjust the Pointer (Tables 8 to 20 Inclusive)

Table 7

CHARACTERISTICS OF OPERATORS

Operator	Age	Weight	Height	Diff. Between Shaft and Elbow Height
1	19	149	5'-10"	Minus 1/8"
2	19	167	5'-11"	Minus 1/4"
3	20	200	6'-2"	Plus 1/8"
4	21	155	5'-9"	Plus 1/8"
5	29	150	5'-11"	Minus 1/4"
6	24	190	6'-2"	Plus 1/8"
7	31	185	5'-11"	Minus 1/4"
8	26	165	6'-0"	Plus 1/4"
9	27	178	5'11"	Minus 1/4"
10	31	135	5'-8"	Minus 1/4"
11	35	165	5'-11"	Minus 1/4"
12	31	135	5'-8"	Minus 1/4"
13	39	175	5'-10"	None

Table 8

Time in Hundredths of Seconds For Adjustment of Pointer

OPERATOR NO. 1

Handwheels

Torques (In-Lbs)	4 in.		5 in.		7 in.		10 in.		14 in.	
108.15	----		----		50	43	74	66	67	67
	----		----		127	76	77	70	38	66
	----		----		58	44	67	67	61	81
	----		----		83	64	58	51	72	58
	----		----		63	59	39	66	91	71
55.35	89	86	62	49	51	67	95	48	51	31
	97	105	44	56	49	101	56	73	56	86
	197	65	102	48	47	56	49	52	69	55
	86	64	70	86	48	81	58	56	31	47
	87	87	134	88	56	59	43	78	71	74
28.20	60	41	56	85	51	37	95	48	51	31
	66	57	29	49	39	38	56	73	56	86
	58	65	38	25	43	70	49	52	69	55
	29	44	49	45	35	51	58	56	31	47
	55	28	39	39	41	76	43	78	71	74
17.20	35	81	77	41	70	58	62	64	54	24
	51	68	21	71	112	41	82	60	96	82
	33	42	50	23	60	68	83	48	36	31
	45	45	34	44	67	53	28	52	59	30
	96	60	25	45	93	38	55	58	51	38
6.05	51	55	44	67	61	23	46	36	60	57
	42	40	34	36	47	66	78	47	29	31
	36	61	46	16	48	40	23	56	27	27
	31	49	19	19	14	166	23	108	39	83
	----		60	35	40	59	26	24	29	47

Table 9

Time in Hundredths of Seconds For Adjustment of Pointer

OPERATOR NO. 2

Handwheels

Torque (In-Lbs)	4 in.		5 in.		7 in.		10 in.		14 in.	
108.15	----		----		94	85	42	42	73	44
	----		----		89	78	42	45	65	53
	----		----		96	126	45	45	66	49
	----		----		97	81	38	50	55	78
	----		----		73	76	42	45	57	48
55.35	108	95	75	68	52	62	35	56	44	69
	87	93	80	78	59	82	40	43	29	40
	97	112	75	75	43	55	44	36	49	40
	79	80	77	65	56	73	51	46	33	39
	76	82	71	86	67	59	48	54	36	73
28.20	99	87	39	44	38	38	26	23	61	39
	106	76	58	48	35	39	52	27	36	34
	101	69	53	58	33	39	36	46	40	64
	74	89	57	64	37	42	25	24	56	38
	189	60	41	72	26	48	24	41	40	40
17.20	62	89	35	45	19	25	57	35	33	37
	78	70	24	40	52	27	40	54	30	60
	74	72	55	44	25	29	48	38	39	40
	63	64	53	37	25	30	46	43	59	34
	58	59	59	42	27	44	39	36	42	63
6.05	49	70	53	26	49	84	23	23	57	31
	39	54	29	25	35	50	23	24	39	61
	82	48	48	41	46	48	22	24	38	35
	62	64	36	25	48	36	24	41	37	47
	60	54	31	106	44	39	25	44	77	43

Table 10

Time in Hundredths of Seconds
For Adjustment of Pointer

OPERATOR NO. 3

Handwheels

Torque (In-Lbs)	4 in.		5 in.		7 in.		10 in.		14 in.	
108.15	----		----		97	128	89	86	89	69
	----		----		124	86	83	80	79	63
	----		----		90	89	92	85	82	93
	----		----		90	87	85	106	65	70
	----		----		114	82	79	86	72	71
55.35	108	115	84	81	64	55	76	70	54	60
	98	98	74	76	59	94	76	59	62	99
	121	96	78	81	64	49	74	67	62	55
	81	93	78	83	63	43	70	60	65	55
	100	98	72	84	--	52	69	67	56	59
27.20	87	60	52	42	28	60	53	47	51	43
	92	74	35	43	73	47	51	48	72	53
	73	82	41	30	24	47	48	71	42	62
	74	43	38	38	38	43	74	107	48	47
	70	58	45	61	40	51	59	54	44	46
17.20	60	47	37	41	50	56	28	48	66	60
	60	64	39	35	51	52	49	47	49	62
	45	54	32	49	63	36	43	45	55	64
	51	65	41	37	101	67	37	59	54	54
	51	64	35	68	61	65	42	56	53	64
6.05	51	58	43	37	85	106	42	45	52	95
	50	44	41	41	47	26	38	27	44	46
	48	50	77	40	31	31	38	55	70	55
	52	44	44	57	57	51	54	31	48	43
	37	52	89	42	42	51	33	23	72	77

Table 11

Time in Hundredths of Seconds
For Adjustment of Pointer

OPERATOR NO. 4

Torque (In-Lbs)	4 in.		5 in.		7 in.		10 in.		14 in.	
108.15	----		----		69	47	72	56	74	75
	----		----		45	61	65	101	101	70
	----		----		89	49	54	63	118	87
	----		----		77	50	57	59	79	81
	----		----		56	50	87	70	67	82
55.35	83	108	73	72	62	60	75	58	80	82
	85	106	63	93	51	53	75	118	75	121
	99	114	92	66	58	51	56	89	67	84
	92	113	185	62	79	69	80	48	126	68
	153	110	87	80	59	65	77	51	100	81
28.20	52	60	47	56	34	42	65	53	82	87
	60	97	43	46	53	89	77	56	77	78
	74	104	142	59	37	32	50	51	100	54
	52	59	94	44	35	68	70	56	48	63
	50	76	69	34	60	39	58	59	97	56
17.20	52	60	93	64	38	53	66	54	45	60
	65	42	78	86	54	56	44	29	68	53
	42	60	78	63	18	42	59	49	73	58
	54	65	66	51	45	49	36	88	104	67
	62	46	66	94	38	49	64	52	52	56
6.05	61	26	54	48	69	74	60	69	71	25
	60	20	50	27	51	35	38	55	101	68
	56	26	47	104	66	35	44	41	48	101
	54	54	69	26	60	29	43	44	100	74
	70	44	57	43	39	51	37	37	90	85

Table 12

Time in Hundredths of Seconds For Adjustment of Pointer

OPERATOR NO. 5

Handwheels

Torque (In-Lbs)	4 in.		5 in.		7 in.		10 in.		14 in.	
108.15	----		----		62	67	58	32	109	67
	----		----		67	59	53	36	66	49
	----		----		68	65	56	64	86	57
	----		----		59	89	49	50	62	37
	----		----		72	80	49	72	62	46
55.35	112	101	108	66	56	66	62	46	50	46
	86	76	68	97	52	53	51	45	65	59
	87	80	71	52	49	47	46	53	50	--
	70	98	74	72	67	44	53	52	61	--
	97	112	64	72	44	73	56	62	67	--
28.20	61	41	49	44	65	48	41	37	44	52
	84	57	39	33	52	111	23	17	53	57
	80	53	30	79	53	56	23	17	60	64
	51	45	31	80	47	41	41	41	37	70
	50	49	44	73	47	41	32	17	39	42
17.20	49	41	44	41	36	37	64	20	67	32
	52	65	70	48	73	38	37	66	60	35
	38	53	51	42	43	49	46	17	60	34
	37	51	48	47	44	39	34	22	60	37
	47	49	47	63	39	38	39	16	42	56
6.05	72	39	59	44	76	47	26	37	44	51
	35	64	48	29	35	45	24	23	57	34
	37	--	46	26	46	46	24	21	58	29
	20	56	29	56	49	50	41	20	37	27
	55	49	38	50	44	35	36	31	35	36

Table 13

Time in Hundredths of Seconds For Adjustment of Pointer

OPERATOR NO. 6

Handwheels

Torque (In-Lbs)	4 in.		5 in.		7 in.		10 in.		14 in.	
106.15	----		----		58	84	65	96	83	74
	----		----		58	103	64	63	85	66
	----		----		89	73	66	67	80	69
	----		----		88	88	66	64	59	68
	----		----		79	77	66	49	107	87
55.35	86	80	56	70	69	91	47	69	67	65
	82	102	60	70	77	78	74	66	71	71
	74	92	62	54	77	73	41	49	74	71
	129	140	51	53	67	99	71	47	93	75
	101	87	56	59	120	71	96	49	60	57
28.20	93	82	80	47	109	49	39	81	118	67
	73	63	53	56	63	67	52	57	91	64
	62	64	67	41	63	82	68	39	54	66
	63	89	56	43	113	71	57	36	62	61
	64	79	59	36	77	60	41	38	67	64
17.20	74	75	64	47	92	50	71	73	53	79
	73	66	54	53	51	55	120	50	71	73
	70	74	44	51	68	45	69	46	89	68
	88	71	51	51	56	73	73	44	59	72
	69	65	37	41	47	61	74	42	66	66
6.05	39	74	44	38	53	40	45	54	62	56
	68	64	39	37	25	25	38	47	89	109
	74	67	47	53	47	29	38	43	56	56
	55	66	40	52	30	77	72	44	50	64
	66	64	24	40	59	64	80	48	49	51

Table 14

Time in Hundredths of Seconds For Adjustment of Pointer

OPERATOR NO. 7

Handwheels

Torque (In-Lbs)	4 in.		5 in.		7 in.		10 in.		14 in.	
108.15	----		----		70	35	60	149	48	19
	----		----		92	75	85	45	58	27
	----		----		58	103	56	98	65	19
	----		----		44	51	51	48	51	24
	----		----		75	76	63	57	20	53
55.35	88	61	51	31	58	26	65	53	43	22
	56	62	53	34	38	52	40	60	54	17
	84	77	63	43	12	37	21	68	33	45
	106	42	36	34	28	93	22	63	20	21
	68	75	30	61	46	76	26	34	51	30
28.20	85	32	19	17	19	46	63	37	22	39
	39	41	44	47	48	40	35	36	51	44
	62	60	56	31	17	38	48	38	41	25
	30	32	64	47	47	23	69	16	42	32
	53	30	29	23	33	28	44	30	42	51
17.20	31	51	33	51	41	41	79	56	49	53
	66	38	13	25	48	33	35	34	19	36
	55	37	06	22	28	21	65	81	21	34
	46	38	36	21	23	28	26	44	41	23
	72	33	06	10	14	43	17	74	48	25
6.05	57	11	51	27	39	19	26	29	52	44
	66	39	20	69	14	39	38	26	34	22
	52	32	45	34	20	33	32	33	59	27
	64	24	31	35	19	66	70	55	40	54
	19	62	49	27	17	66	27	32	31	49

Table 15

Time in Hundredths of Seconds For Adjustment of Pointer

OPERATOR NO. 8

Handwheels

Torque (In-Lbs)	4 in.		5 in.		7 in.		10 in.		14 in.	
108.15	----		----		76	73	57	39	72	68
	----		----		88	83	77	38	76	90
	----		----		91	56	75	67	77	81
	----		----		89	60	47	45	78	71
	----		----		112	88	45	45	60	55
55.35	119	118	65	63	73	88	67	68	124	81
	236	89	58	67	78	84	79	64	96	60
	103	115	118	72	113	106	57	78	74	60
	107	113	69	51	79	103	74	65	68	64
	111	89	74	94	108	85	62	66	53	60
28.20	58	81	40	48	51	71	39	28	49	60
	63	70	64	71	70	51	57	28	35	56
	86	75	45	63	79	64	44	43	36	38
	76	62	29	41	70	66	42	24	28	60
	72	48	46	57	76	42	42	43	47	47
17.20	83	57	64	61	47	69	62	40	38	47
	83	66	53	50	123	63	68	35	27	82
	75	49	67	67	54	26	21	50	24	70
	79	62	67	76	51	46	56	53	34	43
	83	76	60	52	71	39	39	107	37	37
6.05	52	40	50	41	52	21	53	26	68	35
	48	42	32	16	38	18	58	23	40	42
	38	44	35	34	44	67	35	20	71	45
	45	96	27	23	46	40	51	38	48	49
	34	91	13	42	41	56	57	13	42	44

Table 16

Time in Hundredths of Seconds For Adjustment of Pointer

OPERATOR NO. 9

Handwheels

Torque (In-Lbs)	4 in.		5 in.		7 in.		10 in.		14 in.	
108.15	----		----		65	56	74	61	76	58
	----		----		67	67	56	69	67	60
	----		----		60	59	52	60	62	60
	----		----		64	50	51	45	62	71
	----		----		66	50	49	39	60	107
55.35	61	60	57	62	66	59	37	35	66	39
	65	57	45	52	57	52	34	54	45	37
	58	73	52	45	66	91	79	58	35	41
	66	57	34	44	53	54	41	62	52	32
	51	67	59	39	64	59	50	30	41	52
28.20	59	59	62	37	40	34	50	50	49	48
	80	63	40	36	27	41	35	32	39	65
	95	49	42	35	38	15	43	35	40	38
	60	50	42	44	34	37	37	45	66	64
	57	64	41	53	37	36	44	55	40	39
17.20	56	35	40	31	50	17	63	39	47	55
	56	58	28	35	49	26	45	37	31	36
	49	35	22	42	25	14	42	42	35	42
	55	38	44	40	31	19	54	27	36	36
	58	36	37	24	32	16	46	45	56	36
6.05	45	29	33	31	20	52	21	36	68	27
	50	35	34	33	08	32	20	24	25	37
	35	43	29	34	50	34	42	51	47	39
	22	62	18	35	55	25	48	25	26	27
	33	36	31	46	31	27	68	19	30	--

Table 17

Time in Hundredths of Seconds For Adjustment of Pointer

OPERATOR NO. 10

Handwheels

Torque (In-Lbs)	4 in.		5 in.		7 in.		10 in.		14 in.	
108.15	----		----		45	64	75	73	80	65
	----		----		43	57	150	55	52	50
	----		----		36	59	71	70	65	56
	----		----		44	72	78	52	45	61
	----		----		67	61	64	49	63	56
55.35	126	228	75	85	51	122	55	68	93	54
	105	112	92	78	50	54	49	44	79	69
	135	100	72	51	48	62	52	40	69	54
	111	252	80	64	36	52	38	52	39	44
	100	113	86	60	57	63	45	65	35	36
28.20	77	84	58	45	64	38	80	34	33	45
	83	84	58	42	59	68	84	105	74	68
	90	92	43	38	56	34	64	69	112	56
	93	85	37	62	54	67	30	61	69	50
	92	84	59	47	78	21	56	63	73	104
17.20	83	71	41	45	26	37	41	58	100	41
	76	67	44	40	57	46	57	57	45	43
	70	71	37	47	62	40	58	43	47	105
	63	57	40	44	58	50	62	51	41	46
	56	63	39	43	40	66	31	55	44	81
6.05	74	76	69	45	59	26	57	67	35	50
	57	92	39	44	48	26	40	21	75	44
	63	83	46	55	44	37	30	60	43	40
	100	52	46	47	59	24	25	49	43	78
	96	85	39	54	24	34	98	24	65	73

Table 18

Time in Hundredths of Seconds
For Adjustment of Pointer

OPERATOR NO. 11

Torque (In-Lbs)	4 in.		5 in.		7 in.		10 in.		14 in.	
108.15	----		----		79	78	61	60	49	29
	----		----		52	54	59	52	40	44
	----		----		102	56	45	81	53	38
	----		----		69	75	54	37	48	30
	----		----		58	50	50	44	31	65
55.35	75	76	55	39	62	74	47	115	27	26
	72	67	51	24	66	25	53	61	37	31
	56	58	51	44	29	75	27	38	36	33
	56	57	56	24	46	33	59	44	122	70
	170	71	27	89	143	118	24	91	32	35
28.20	38	47	127	42	72	34	46	44	56	30
	16	36	62	48	36	87	61	25	27	29
	34	16	53	30	18	28	47	26	51	26
	118	41	49	28	120	32	39	134	41	34
	39	34	58	44	115	25	42	43	31	65
17.20	34	36	43	12	42	19	20	42	60	61
	108	37	27	92	38	43	20	14	54	35
	35	52	33	31	60	55	63	22	32	55
	29	36	89	08	37	135	24	51	30	41
	108	75	25	96	44	37	41	17	64	55
6.05	34	28	55	55	20	26	105	45	66	34
	28	37	26	35	59	18	100	39	42	36
	36	11	04	41	15	83	23	85	36	59
	15	40	41	30	64	41	55	33	70	41
	74	22	26	08	36	94	44	20	68	30

Table 19

Time in Hundredths of Seconds For Adjustment of Pointer

OPERATOR NO. 12

Handwheels

Torque (In-Lbs)	4 in.		5 in.		7 in.		10 in.		14 in.	
108.15	----		----		105	73	44	79	130	32
	----		----		68	37	37	43	61	51
	----		----		35	38	51	110	30	51
	----		----		57	52	57	20	104	60
	----		----		87	96	39	19	51	32
55.35	71	68	59	41	40	30	40	91	44	26
	53	65	88	45	42	44	97	36	47	23
	68	109	30	38	48	25	27	17	39	24
	46	88	28	62	53	55	23	14	24	56
	61	73	124	81	47	27	31	42	41	51
28.20	44	51	51	35	89	35	40	11	44	60
	64	67	40	41	37	50	48	39	52	50
	79	30	107	45	26	20	42	101	35	25
	29	18	48	47	21	20	34	64	52	25
	22	32	31	45	72	41	34	29	53	56
17.20	45	44	99	45	25	23	13	54	45	31
	40	40	44	36	24	71	75	35	97	26
	52	34	76	34	16	10	24	30	45	21
	29	36	104	42	40	25	35	31	34	20
	38	40	92	36	44	12	26	19	30	50
6.05	38	20	60	27	11	26	71	29	53	30
	86	12	23	25	34	14	32	17	45	25
	25	34	62	28	24	15	52	27	58	59
	37	11	22	09	34	72	39	15	58	22
	32	28	24	45	26	39	25	12	34	44

Table 20

Time in Hundredths of Seconds
For Adjustment of Pointer

OPERATOR NO. 13

Handwheels

Torque (In-Lbs)	4 in.		5 in.		7 in.		10 in.		14 in.	
108.15	----		----		49	60	57	51	51	77
	----		----		59	61	51	39	58	51
	----		----		54	62	53	50	60	76
	----		----		56	64	49	56	64	75
	----		----		58	44	53	56	57	65
55.35	70	60	78	71	50	44	43	52	120	69
	76	62	61	73	57	56	47	53	61	73
	113	57	57	57	57	65	50	46	57	75
	90	73	49	53	51	56	42	53	64	70
	59	72	52	55	43	41	38	40	84	83
28.20	72	63	46	48	38	50	39	37	76	60
	73	88	61	53	44	59	31	63	40	64
	42	55	58	59	36	38	58	39	71	89
	86	67	39	47	40	36	27	56	65	57
	85	52	57	39	36	38	37	48	57	64
17.20	49	60	60	55	37	48	60	47	101	70
	50	44	89	53	41	42	44	39	97	78
	59	52	81	45	47	31	38	35	57	55
	43	35	68	44	40	49	73	45	55	44
	44	42	63	40	49	53	48	35	86	57
6.05	41	33	112	38	32	35	26	42	70	134
	78	40	68	51	25	35	43	32	93	63
	48	68	89	50	42	24	66	34	81	61
	43	72	49	58	48	42	50	41	62	59
	48	98	54	51	24	40	62	37	89	54

APPENDIX B

Tables of Sums of Times
(Tables 21 to 23 Inclusive)

And a Summary of Calculations
To Show that the Variables Were Significant

Table 21

SUMS OF TIMES IN SECONDS FOR ALL HANDWHEELS

	Torques				
Operators	55.35	28.20	17.20	6.05	T_o
1	3.496	2.507	2.740	2.302	11.045
2	3.172	2.631	2.299	2.219	10.321
3	3.717	2.709	2.617	2.512	11.555
4	4.154	3.144	2.906	2.736	12.940
5	3.298	2.441	2.263	2.063	10.065
6	3.699	3.256	3.174	2.651	12.780
7	2.409	1.985	1.874	1.926	8.194
8	4.268	2.681	2.889	2.089	11.927
9	2.630	2.321	1.948	1.764	8.663
10	3.800	3.183	2.685	2.660	12.328
11	2.877	2.424	2.317	2.133	9.751
12	2.474	2.229	1.997	1.688	8.388
13	3.042	2.683	2.677	2.735	11.137
T_t:	43.036	34.194	32.386	29.478	T= 139.094

$\Sigma T_{to}^2 = 389.731900$

Table 22

SUMS OF TIMES IN SECONDS FOR ALL TORQUES

Handwheels

Operators	4"	5"	7"	10"	14"	T_o
1	2.488	2.000	2.320	2.213	2.024	11.045
2	3.130	2.138	1.765	1.486	1.802	10.521
3	2.768	2.141	2.188	2.140	2.318	11.555
4	2.766	2.771	2.047	2.331	3.025	12.940
5	2.436	2.172	2.021	1.459	1.977	10.065
6	3.067	2.048	2.623	2.286	2.756	12.780
7	2.077	1.424	1.460	1.747	1.486	8.194
8	3.094	2.165	2.569	1.980	2.119	11.927
9	2.117	1.588	1.553	1.700	1.705	8.663
10	3.698	2.136	1.997	2.138	2.359	12.328
11	2.032	1.778	2.204	1.929	1.808	9.751
12	1.817	2.019	1.407	1.491	1.654	8.388
13	2.462	2.295	1.719	1.796	2.865	11.137
T_w:	33.952	26.675	25.873	24.696	27.898	T=139.094

$\Sigma T_{wo}^2 = 312.419198$

$\Sigma T_w^2 = 3921.896878$

$\Sigma T_o^2 = 1520.004748$

Table 23

SUMS OF TIMES IN SECONDS FOR ALL OPERATORS

Handwheels

Torques	4"	5"	7"	10"	14"	T_t
55.35	11.913	8.513	7.987	7.144	7.479	43.036
27.20	8.341	6.439	6.361	6.134	6.919	34.194
17.20	7.281	6.277	5.956	6.161	6.711	32.386
6.05	6.417	5.446	5.569	5.257	6.789	29.478
T_w:	33.952	26.675	25.873	24.696	27.898	T= 139.094

$\Sigma T_{wt}^2 = 1008.609128$

$\Sigma T_t^2 = 4939.132412$

SUMMARY OF CALCULATIONS

Total Sum of Squares $= \Sigma X^2_{wot} - \frac{T^2}{260} = 7.030433$

Subtotal Sum of Squares (w x o) $= \frac{\Sigma T^2_{wo}}{4} - \frac{T^2}{260} = 3.692719$

Wheels Sum of Squares $= \frac{\Sigma T^2_w}{65} - \frac{T^2}{260} = 1.009014$

Operator Sum of Squares $= \frac{\Sigma T^2_o}{20} - \frac{T^2}{260} = 1.588157$

Wheels x Operators Sum of Squares = Subtotal S.S. (w x o)
less Wheels S.S.
less Operator S.S.
= 1.095548

Subtotal Sum of Squares (o x t) $= \frac{\Sigma T^2_{to}}{5} - \frac{T^2}{260} = 3.534300$

Operators x Torques Sum of Squares = Subtotal S.S. (o x t)
less Operator S.S.
less Torque S.S.
= 0.371571

Error (t x o x w) = Total S.S. - (Wheel S.S. + Torque S.S.
+ Operator S.S.
+ Wheel x Torque S.S.
+ Wheel x Op. S.S.
+ Torque x Op. S.S.)
= 0.801920

Subtotal S.S. (w x t) $= \frac{\Sigma T^2_{wt}}{13} - \frac{T^2}{260} = 3.173238$

Torque Sum of Squares $= \frac{\Sigma T^2_t}{65} - \frac{T^2}{260} = 1.574572$

Wheels x Torque Sum of Squares = Subtotal S.S. (w x t)
- Torque S.S. - Wheels S.S.
= 0.589652

Table 24

RESULTS OF F-TESTS

Sources	Deg. of Freedom	Sum of Squares	Mean Square	F	F_{05}	F_{01}
Wheels	4	1.009014	0.252257	11.052	2.56	3.74
Torques	3	1.574572	0.524857	50.652	2.86	4.38
Operators	12	1.588157	0.132346	4.153	1.85	2.37
w x t	12	0.589652	0.049138	8.971	1.82	2.30
w x o	48	1.095548	0.022824	4.167	1.45	1.67
Error (wxtxo)	144	0.801920	0.005569			
Total:	259	7.030423	0.027144			

Hypothesis 1: The wheel effects are zero.

$$F = \frac{\text{Wheel M.S.}}{\text{Wheel x Oper. M.S.}} = 11.052$$

$n_1 = 4$ $F_{05} = 2.56$
$n_2 = 48$ $F_{01} = 3.74$

Since 11.052 > 2.56, the hypothesis is rejected; thus we can say, at the 1 per-cent level, that the wheels are significantly different.

Hypothesis 2: The torque effects are zero.

$$F = \frac{\text{Torque M.S.}}{\text{Torque x Oper. M.S.}} = 50.652$$

$n_1 = 3$ $F_{05} = 2.86$
$n_2 = 36$ $F_{01} = 4.38$

Since 50.652 > 4.38, the hypothesis is rejected; thus we can say, at the 1 per-cent level, that the torques are significantly different.

Table 24 (Continued)

Hypothesis 3: The operator effects are zero.

$$F = \frac{(\text{Operator M.S.}) + (\text{Error M.S.})}{(\text{Wheel x Op. M.S.}) + (\text{Torque x Op. M.S.})} = 4.153$$

$$n_1 = \frac{(\text{Operator M.S.} + \text{Error M.S.})^2}{\frac{(\text{Operator M.S.})^2}{\text{deg. of free.}} + \frac{(\text{Error M.S.})^2}{\text{deg. of free.}}} = 13$$

$$n_2 = \frac{(\text{wheel x operator M.S.} + \text{Torque x Oper.M.S.})^2}{\frac{(\text{wheel x oper. M.S.})^2}{\text{deg. of freedom}} + \frac{(\text{Torque x Oper.M.S.})^2}{\text{deg. of freedom}}} = 80$$

$F_{05} = 1.85$ $F_{01} = 2.37$

Since $4.153 > 2.37$, the hypothesis is rejected; thus we can say, at the 1 per-cent level, that the operators are significantly different.

Hypothesis 4: Interaction effects of wheels and torques is zero.

$$F = \frac{\text{wheels x torques M.S.}}{\text{Error M.S.}} = 8.971$$

$n_1 = 12$ $F_{05} = 1.82$
$n_2 = 144$ $F_{01} = 2.30$

Since $8.971 > 2.30$, the hypothesis is rejected; thus, we can say, at the 1 per-cent level, that the interaction effects of the wheels and torques are significant.

Hypothesis 5: Interaction effects of wheels and operators are zero.

$$F = \frac{\text{wheels x operators M.S.}}{\text{Error M.S.}} = 4.167$$

$n_1 = 48$ $F_{05} = 1.45$
$n_2 = 144$ $F_{01} = 1.67$

Since $4.167 > 1.67$, the hypothesis is rejected; thus, we can say, at the 1 per-cent level, that the interaction effects of wheels and operators are significant.

Table 24 (Continued)

Hypothesis 6: Interaction effects of torques and operators are zero.

$$F = \frac{\text{torques x operators M.S.}}{\text{Error M.S.}} = 1.854$$

$n_1 = 36$ $F_{05} = 1.54$
$n_2 = 144$ $F_{01} = 1.84$

Since 1.854 $>$ 1.84, the hypothesis is rejected; thus, we can say, at the 1 per-cent level, that the interaction effects of the torques and operators are statistically significant.

APPENDIX C

Data and Calculations for Curve Fitting

Table 25

Summary of Data Derived from Mean Times (Tables 2 to 6)

HANDWHEELS

	4"	5"	7"
T	33.952	26.675	35.035
$\frac{T^2}{\text{oper. x tor.}}$	22.168044	13.683762	18.883865
ΣY^2_{to}	24.738988	14.679377	20.485455
$\frac{\Sigma T^2_o}{\text{operators}}$	23.5140538	14.0762719	19.591110
$\frac{\Sigma T^2_t}{\text{torques}}$	22.793956	14.0122912	19.3944490
ΣX	1388.40	1388.40	2794.35
ΣX^2	54486.965	54486.965	206534
ΣXY	1058.6568	793.687	1748.4666
ΣX^3	------	------	18853147
ΣX^4	------	------	145628476
ΣX^2Y	------	------	136919.786

	10"	14"
T	32.594	36.215
$\frac{T^2}{\text{oper. x tor.}}$	16.344136	20.1773265
ΣY^2_{to}	17.326714	20.959484
$\frac{\Sigma T^2_o}{\text{operators}}$	16.664236	20.316041
$\frac{\Sigma T^2_t}{\text{torques}}$	16.735531	20.998687
ΣX	2794.35	2794.35
ΣX^2	206534	206534
ΣXY	1560.34195	1665.06465

Table 26

Summary of Tests of Significance for Fitted Curves for Handwheels

4 Inch Handwheel

Source	D.F.	S.S.	M.S.	F	F_{05}
Torque	3	1.3460098			
Linear	1	1.328963			
Dep. from Linear	2	0.0170468	0.0085234	0.5122	3.26
Within Torques	48	1.224935			
Operators	12	0.625912			
Error	36	0.599023	0.01663952		
Total		2.570944			

5 Inch Handwheel

Source	D.F.	S.S.	M.S.	F	F_{05}
Torque	3	0.392509			
Linear	1	0.389530			
Dep. from Linear	2	0.002979	0.001489	0.1952	3.26
Within Torques	48	0.603106			
Operators	12	0.328529			
Error	36	0.274577	0.00762713		
Total		0.995615			

7 Inch Handwheel

Source	D.F.	S.S.	M.S.	F	F_{05}
Torques	4	0.707245			
Linear	1	0.5596396			
Dep. from Linear	3	0.1476054	0.0492018	6.1533	2.80
Parabola	2	0.707031			
Dep. from Parabola	2	0.000214	0.000107	0.0134	2.80
Within Torques	60	0.894345			
Operators	12	0.510584			
Error	48	0.383797			
Total		1.601590			

Table 26

Summary of Tests of Significance for Fitted Curves for Handwheels (Cont'd)

Source	D.F.	S.S.	M.S.	F	F_{05}
Torques	4	0.320100			
Linear	1	0.2930739			
Dep. from Linear	3	0.027026	0.0090087	1.595	2.80
Within Torques	60	0.662478			
Operators	12	0.391395			
Error	48	0.271083	0.00564756		
Total		0.982578			

Source	D.F.	S.S.	M.S.	F	F_{05}
Torques	4	0.1387145			
Linear	1	0.13548225			
Dep. from Linear	3	0.003232257	0.00107741	0.5069	2.800
Within Torques	60	0.643443			
Operators	12	0.5414405			
Error	48	0.1020025	0.0021251		
Total		0.7821575			

Sample Calculations Used to Fit Curves And Test for Goodness of Fit

Seven-Inch Handwheel:

Hypothesis 1: The observed data may be represented by a linear curve.

S.S. due to torques $= \dfrac{\Sigma T_t^2}{13} - \dfrac{T^2}{65} = 0.707245$

Normal Equations for Linear Curve:

$$\begin{aligned} 65a + b\Sigma X &= T \\ a\Sigma X + b\Sigma X^2 &= \Sigma XY \\ \hline 65a + 2794.35b &= 32.594 \\ 2794.35a + 206534b &= 1560.34195 \\ \hline a &= 0.422275 \\ b &= 0.00184162 \end{aligned}$$

The Estimating Equation is:

$$Y_c = 0.422275 + 0.00184162\ X$$

S.S. Due to Linear Curve

$= 13\ \Sigma(a + bX)^2 - \dfrac{T^2}{65} = 0.5596396$

S.S. Due to Departure from Linear Curve:

$=$ Torque S.S. - S.S. due to Linear $= 0.1476054$

Total S.S. $= \Sigma Y_{to}^2 - \dfrac{T^2}{65} = 1.60159$

Within Torques S.S. = Total S.S. - Torque S.S.
= 0.894345

S.S. due to operators $= \dfrac{\Sigma T_o^2}{5} - \dfrac{T^2}{65} = 0.510584$

Error S.S. = S.S. within torques - Operator S.S.
= 0.383797

Applying the F Test:

$$F = \frac{\text{M.S. (Dep. from linear)}}{\text{M.S. (Error)}} = 6.1533$$

$n_1 = 3$ $\qquad$ $F_{05} = 2.80$

$n_2 = 48$ $\qquad$ $F_{01} = 4.22$

Since $6.153 > 4.22$, the hypothesis is rejected; then we can say, at the 1 per-cent level, that the observed data cannot be represented by a straight line.

Hypothesis 2: The observed data may be represented by a parabola.

Normal Equations for a parabola:

$$65a + b\Sigma X + c\Sigma X^2 = T$$

$$a\Sigma X + b\Sigma X^2 + c\Sigma X^3 = \Sigma XY$$

$$a\Sigma X^2 + b\Sigma X^3 + c\Sigma X^4 = \Sigma X^2 Y$$

$$65a + 2794.35b + 206534c = 35.035$$

$$2794.35a + 206534b + 18853147c = 1748.4666$$

$$206534\,a + 18853147b + 145628476c = 136919.786$$

$a = 0.4254638$

$b = 0.002584573$

$c = 0.000001366834$

The Estimating Equation Is:

$$Yc = 0.4254638 + 0.002584573X + 0.000001366834X^2$$

$$\text{S.S. due to parabola} = 13\Sigma(a + bX + cX^2) - \frac{T^2}{65} = 0.707031$$

S.S. due to departure from parabola

= Torque S.S. - S.S. due to parabola

= 0.000214

Applying the F Test:

$$F = \frac{\text{M.S.(Dep. from Parabola)}}{\text{M.S.(Error)}} = 0.013382$$

$n_1 = 2$ $\qquad$ $F_{05} = 3.19$

$n_2 = 48$ $\qquad$ $F_{01} = 5.08$

Since $0.013382 < 3.19$, the hypothesis is substantiated; thus we can say, at the 5 per-cent level, that the data can be represented by a parabola.

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